Systems Engineering for Space Exploration Medical Capabilities

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Human exploration missions to beyond low Earth orbit destinations such as Mars will present significant new challenges to crew health management during a mission compared to current low Earth orbit operations. For the medical system, lack of consumable resupply, evacuation opportunities, and real-time ground support are key drivers toward greater autonomy. Recognition of the limited mission and vehicle resources available to carry out exploration missions motivates the Exploration Medical Capability (ExMC) Element's approach to enabling the necessary autonomy. The Element's work must integrate with the overall exploration mission and vehicle design efforts to successfully provide exploration medical capabilities. ExMC is applying systems engineering principles and practices to accomplish its integrative goals. This paper discusses the structured and integrative approach that is guiding the medical system technical development. Assumptions for the required levels of care on exploration missions, medical system guiding principles, and a Concept of Operations are early products that capture and clarify stakeholder expectations. Mobel-Based Systems Engineering techniques are then applied to define medical system behavior and architecture. Interfaces to other flight and ground systems, and within the medical system are identified and defined. Initial requirements and traceability are established, which sets the stage for identification of future technology development needs. An early approach for verification and validation, taking advantage of terrestrial and near-Earth exploration system analogs, is also defined to further guide system planning and development.

Nomenclature

ConOps	=	Concept of Operations
ExMC	=	Exploration Medical Capabilities
MBSE	=	Model-Based Systems Engineering
NASA	=	National Aeronautics and Space Administration
SysML	=	Systems Modeling Language

I. Introduction

EXPLORATION missions beyond low earth orbit bring opportunities for human capability development, and challenges in the development of those enabling capabilities. A driving case of a human mission to Mars will be longer than human space missions to date, and also will lack the medical evacuation, real-time communication, and

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resupply more readily available for current low-Earth orbit operations. In addition, predicting the exact medical conditions for which to plan will not be possible. Therefore, an exploration medical system must provide flexible capabilities to support the care of crewmembers with conditions that were not considered specifically in advance. Medical technologies to be considered in exploration designs will continue to rapidly evolve for the foreseeable future, so the design framework must allow for new technologies. Limited flight resources such as mass, power, volume, and data, are constraints requiring the medical system to be viewed as an integrated part of flight system development for exploration. A systems engineering approach is required to meet the exploration crew health management needs within opposing constraints. The Exploration Medical Capability (ExMC) element of NASA's Human Research Program is undertaking these systems engineering activities [1, 2].

II. Systems Engineering Approach for the Medical System

A. Systems Engineering Management Approach

There are many ways to approach the practice of systems engineering principles. As the ExMC Systems Engineering team was established, a Systems Engineering Management Plan, tailored from the NASA Systems Engineering Handbook [3], was developed to capture context, approach and execution information. A summary of key points and the team mission description will be provided here.

B. Application of Model-Based Systems Engineering

ExMC is utilizing Model-Based Systems Engineering (MBSE) to support medical system design, analysis, verification and validation activities that will inform research activity needs and prioritization. Using a traditional document-based approach to systems engineering can result in cost increases, raise technical risk and create information silos among teams. The ExMC system engineering team's use of MBSE, in conjunction with the System Modeling Language and other systems engineering tools, improves quality of technical products and communication through the use of shared mental models of the medical system, consistent notation and integrated data sets. These system models will be integral for successful integration of the medical system with exploration vehicles and system verification and validation using terrestrial analogs and precursor exploration missions.

C. Initial Process Overview

The scope of developing an exploration medical system is a large one. At this early stage, the ExMC Systems Engineering team activities must focus on establishing highly valuable technical products and an infrastructure to support the continued development of additional products later in the medical system life cycle. This section will discuss the initial process the systems engineering team is following.

III. Medical System Stakeholder Expectations

A. Level of Care Assumptions

NASA medical care standards establish requirements for providing health and medical programs for crewmembers during all phases of a mission. These requirements are intended to prevent or mitigate negative health consequences of long-duration spaceflight, thereby optimizing crew health and performance over the course of the mission. Current standards are documented in the two volumes of the NASA-STD-3001 Space Flight Human-System Standard document, established by the Office of the Chief Health and Medical Officer. Their purpose is to provide uniform technical standards for the design, selection, and application of medical hardware, software, processes, procedures, practices, and methods for human-rated systems. NASA-STD-3001 Vol. 1 [4] identifies five levels of care for human spaceflight. These levels of care are accompanied by several components that illustrate the type of medical care expected for each.

ExMC has expanded the context of these provided levels of care and components. This supplemental information includes definitions for each component of care and example actions that describe the type of capabilities that coincide with the definition. This interpretation is necessary in order to fully and systematically define the capabilities required for each level of care in order to define the medical requirements and plan for infrastructure needed for medical systems of future exploration missions, such as one to Mars. Examples will be provided here.

B. System Guiding Principles

A set of system guiding principles has been developed to provide a foundation for exploration medical system development. They are based on stakeholder expectations and constraints levied or imposed on the medical system. These principles influence technical measures commonly used for insight into performance of the technical solution, and establish the basis for high-level requirements and quality attributes of the medical system. The list of approximately 7-10 guiding principles and brief descriptions will be included here.

C. Concept of Operations

The Medical System Concept of Operations for Mars Exploration Missions illustrates how a future NASA Mars program could ensure appropriate medical care for the crew of this highly autonomous mission. This Concept of Operations (ConOps) document, when complete, will document all mission phases through a series of mission scenarios that illustrate required medical capabilities, enabling ExMC to plan, design, and prototype an integrated medical system to support human exploration to Mars. The current version of the ConOps contains approximately 10-15 representative scenarios for the Mars transit phase. Each scenario is captured by narrative text and a flow chart of activities. An excerpt of text and an example flow chart will be provided. This content feeds subsequent work using MBSE tools.

IV. Medical System Behavior and Architecture Development

A. Medical System, Crew, and Flight System Activities

Flow charts from the ConOps are analyzed and translated into Activity Diagrams in a SysML model. This clarifies the activities expected to be performed by the medical system, each crewmember (whether in a patient or caregiver role), and the other flight or ground systems. An activity decomposition is modeled to represent activities at various levels of detail for analysis.

B. Functional Decomposition

The activity diagrams and decomposition inform what types of functions the medical system must provide. This information provides a more complete representation of the medical system “problem space”, and examples will be provided here. At the highest level, these functions aid in the development of the medial system architecture, which is the first foray into the “solution space”.

C. Medical System Architecture Overview

With an understanding of what the medical system must do, an architecture is defined. A brief description of the medical system architecture and its constituent aspects will be provided.

D. Interface Identification and Description

The ConOps scenarios are also captured as Sequence Diagrams in the SysML model. This view of the scenarios supports identification of interfaces both outside and within the medical system. Example sequence diagram and interface descriptions, such as an Internal Block Diagram, will be shown here.

V. Initial Requirement and Traceability Development

Requirements are key products for communicating in a common language and integrating with the overall mission and vehicle design. Establishing the ability for requirements and subsequent solution options to be traced to content in key documents, such as NASA-Standard 3001 and the ConOps, will lead to the identification of technology development needs. A brief description of the state of this capability will be given.

VI. Verification and Validation Approach

An early approach for verification and validation, taking advantage of terrestrial and near-Earth exploration system analogs, will be summarized here. It is used to guide system planning and development.

VII. Future Work

This section will include a synopsis of future directions; likely including broader NASA-wide Model-Based Systems Engineering approach coordination.

VIII. Conclusion

Conclusions on the progress of this body of work will be provided here.

Acknowledgments

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